MODELLING OF HOT PRESSING OF MDF

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SUMMARY

The vertical density profile (VDP) has long been recognised as a critical determining factor for the strength and quality of MDF panels. This has led several previous workers to develop phenomenological models to predict the VDP during hot pressing. The models have included the processes of heat and mass transfer within the mat; rheology of the mat during pressing, including creep; kinetics of resin curing. The objective of this, as with previous models, is to assist in obtaining lower energy consumption, better quality pressed boards and more flexible operation in commercial plants.

This paper attempts a more complete integration than hitherto of all these component processes in a one-dimensional model of pressing. The heat and mass transfer part of the model predicts the moisture content changes, temperature profile, partial vapour pressure and total gas pressure across the thickness during closing of the press as well as after the final platen position is reached. The correlation used for the calculation of equilibrium moisture content is an improvement over that used in previous models.

This model includes the mat mechanical and rheological properties, varying with moisture content and temperature under pressing force. The simulation will predict pressing pressure, strain and density across the thickness during pressing, using a Maxwell-element model for stress relaxation and visco-elastic properties. The rate of resin cure at the various temperatures in the panel dictates the relative compression at different points during the press closing. The polymerization kinetics of phenol-formaldehyde resin is included in the model to allow prediction of the rate of resin curing, amount of polymerization during the hot pressing of MDF boards. The use of Matlab to solve the model equations gives a fast solution while providing a very convenient platform for producing graphical results.

The simulations results were validated by experimental measurements in a pilot press. Twenty two MDF boards were made with different pressing parameters and the data collected were compared with the simulation results from the model. The model could predict in an acceptable way the main variables that control the manufacturing of MDF boards. The simulation results for steam injection pressing and new cooling technology in continuous presses is also generated to increase the understanding of internal processes.

INTRODUCTION

Two different approaches to modelling the hot pressing process of wood based composites can be found in the literature. The first is the empirical modelling approach, which employs statistical methods to link material and process variables to output parameters such as the mechanical properties of the final product. The second uses fundamental principles to describe the relevant physical or chemical processes. The second approach will be considered here.

The first heat and mass transfer model based on fundamental physical principles that include vapour convection, heat conduction, convection, and phase change was developed by Humphrey (1982). The model predicted temperature, vapour pressure and moisture content development during hot pressing. The basis of the model was a modified finite difference approach. The predicted data agreed well in trend with those observed experimentally for particleboard.

Hata et al. (1990) described a two dimensional model to calculate the conductive heat flow in absolutely dry particle boards. Under such conditions, which do not occur in practice, vapour convection and moisture effects can be neglected. Hubert and Dai (1998) presented a one dimensional model for simulating hot pressing of OSB using an implicit finite element modelling approach. Mechanisms included were vapour convection, conductive and convective heat, heat transfer, phase change, adhesive cure and mat densification. The visco-elastic behaviour of the mat was neglected. Hubert and Dai (1998) compared model predictions of various parameters with measured data and reported that typical trends were predicted correctly, but that some magnitude discrepancies existed.

For MDF, a three-dimensional unsteady state model was presented by Carvalho and Costa (1998) describing the heat and mass transfer and predicting the spatial and time evolution of temperature, moisture content, steam pressure and relative humidity. Recently, the model developed by Humphrey (1982) for the hot-pressing of particleboard in a batch press has been improved and extended to the continuous process Thomen (2000). However this model ignored the influence of resin cure.

MODEL DEVELOPMENT

The models published by Thomen (2000) and Zombori (2001) were adopted as the basis for further model development. The phenol-formaldehyde resin curing and the heat released from resin curing are included in the heat transfer part of the model. The equations used to calculate relative humidity and equilibrium moisture content have been modified from earlier models. The model is developed specifically for batch and continuous pressing of MDF. Only the main equations used in the model are discussed in this paper.

Assumptions

Several simplifying assumptions have been adopted to solve the problem imposed by the coupled heat and moisture transfer mechanisms during hot-compression. These assumptions are:

1. The model is one dimensional, with changes normal to the platens considered.

2. Solid and gaseous phases are considered, and these two phases are always in local thermodynamic equilibrium.

3. The gas phase located in the voids is composed of an air-water vapour mixture, and the components follow the Ideal Gas Law. Air is treated as a single component gas.

4. Water can be present as bound water in the cell wall or water vapour in the voids. The free water component is ignored due to the low initial mat moisture content typical for wood composite manufacture.

5. The heat supply of the process comes from the hot press platens and from the heat of reaction of the resin.

6. The physical and transport properties are functions of temperature, moisture content, density, porosity, and steam pressure. Therefore they may vary with respect to space and time.

7. The heat is transported by conduction due to temperature differential and by convection due to the vapour flow; the conduction follows Fourier's Law; the heat released from resin curing is included in the model.

8. The two gas phases (air and vapour) are transferred by bulk flow (according to Darcy's Law) and diffusion (according to Fick's Law). The driving force of the bulk flow process is the total pressure differential, while the driving force of diffusion is the partial pressure differential.

9. The migration of the bound water occurs by molecular diffusion due to a gradient in moisture content of the bound water molecules across the thickness.

HEAT AND MASS TRANSFER CALCULATION

Calculation of various transport phenomena in one-dimensional heat and mass flow involves the solution of mass and energy conservation equations. The governing equations describe the physical phenomena involved in a conventional hot-compression process.

Constitute equation for vapour mass conservation:

$$\frac{\partial m}{\partial t} = (-\nabla . j + m_{ev} + m_r) \times V \tag{1}$$

Constitute equation for energy conservation:

$$\frac{\partial T}{\partial t} = \frac{(-\nabla . q - H_v m_{ev} + H_r m_r)}{c_u \rho_u} \tag{2}$$

Constitute equation for moisture conservation:

$$\frac{\partial MC_f}{\partial t} = D_m \frac{\partial^2 MC_f}{\partial x^2} \pm \frac{\partial m_{evap/cond}}{\partial t} \tag{3}$$

EQUILIBRIUM MOISTURE CONTENT

Equilibrium Moisture content (EMC) is defined as the moisture content at which the wood neither gains nor loses moisture at the prevailing temperature and relative humidity. For temperatures above 150 deg C, the equation of Day and Nelson (1965) is more stable and has the following form:

$$EMC = \left[\frac{1}{A} \log_e (1 - \psi) \right]^{\frac{1}{B}} \tag{4}$$

The coefficients in equation (4) can be fitted to experimental data for low temperature (USDA, 1999; Ball et al., 2001) and for high temperatures (Resch et al., 1988; Strickler, 1968). The following fitted coefficients are for average EMC of desorption and adsorption

(Pang, 1997):

$$A = -0.34 \times 10^{-16} T^{5.98} \quad (5)$$

$$B = 348 T^{-0.946} \quad (6)$$

The saturated vapour partial pressure (p_{sat}) at temperature T can be calculated by using fitted correlations from experimental data. On using Yaw's suggestions (Kayihan 1981), the saturated vapour partial pressure is estimated as

$$p_{sat} = \frac{1.0133 \times 10^{5}}{760} \times 10^{f(T)} \quad (7)$$

where $f(T)$ is the following function of temperature:

$$f(T) = 16.3737 - \frac{2818}{T} - 1.6908 \log_{10}(T) - 5.7546 \times 10^{-3} T + 4.007 \times 10^{-6} T^{2} \quad (8)$$

CALCULATION OF VISCOELASTIC PROPERTIES

In the press model developed in this work, the MDF board is divided into a number of thin layers, each of which exhibits uniform properties everywhere. Viscoelastic and physical properties of each layer depend upon the stress-strain behaviour of the layer. A denser layer is the result of more deformation or compression having occurred in that layer. The compressibility of a layer is also affected by temperature and moisture content of the layer. The MDF panel is assumed to be symmetric about the plane of mid-thickness. Thus the equations are solved for only half the panel to speed solution. All layers are assumed to start with the same mass of fibres and the same initial thickness.

The mat behaviour is calculated through a series of time steps during which the board is compressed to the target thickness and then held for a time at that thickness. For each time step, the relative compression in each layer is assumed to be inversely proportional to the modulus of elasticity (MOE) of that layer at the start of the time step. This follows the approach of Suo and Bowyer (1994). They use the term "strain" for ε but their equations show that they use it to mean the change in thickness. They alter the meaning of ε later in their paper.

The relationship between the strain distributed in different layers and their corresponding MOE values can be described as follows:

$$\varepsilon_{1(\Delta t)} : \varepsilon_{2(\Delta t)} : \ldots\ldots : \varepsilon_{i(\Delta t)} : \ldots : \varepsilon_{n(\Delta t)} = \frac{1}{E_{1\,(t-1)}} : \frac{1}{E_{2\,(t-1)}} : \ldots : \frac{1}{E_{i\,(t-1)}} : \ldots : \frac{1}{E_{n\,(t-1)}} \quad (9)$$

By considering the symmetric nature of the panel, the total deformation of the panel in the thickness direction is:

$$2 \sum_{i=1}^{n} d_{i(\Delta t)} = D_{(\Delta t)} \quad (10)$$

where $d_{i(\Delta t)}$ is the displacement induced in layer i during time interval $\Delta t\,(i=1,2,....,n)$, and $D_{(\Delta t)}$ is the total displacement in the mat in the time interval, corresponding to the movement of the platen. $E_{i(t-1)}$ is the modulus of elasticity of layer i at time *t-1*. The value of 2 in equation 10 is to calculate the strain for the whole board, as n is the number of layers in half the board.

Let

$$S = \sum_{i=1}^{n} \frac{1}{E_{i(t-1)}} \qquad (11)$$

Then the displacement induced in each layer can be calculated as follows

$$d_{i(\Delta t)} = \frac{1/E_{i(t-1)}}{S} D_{(\Delta t)} \qquad (12)$$

The MOE of individual fibres can be calculated using the equation derived by Carvalho et al. (2001) who derived the equation using data from Wolcott et al. (1990) under various conditions of temperature and moisture content.

$$E_{i(t)} = E_{fo} \exp\left(-\frac{\beta_T}{T+T_0} + \frac{\beta_H}{H-H_0} \right) \qquad (13)$$

In which the parameters are: $\beta_T = -1820\,^0C$, $\beta_H = 0.0695$, $T_0 = 447^0C$, $H_0 = 0.2925$, $E_{fo} = 6.74MPa$. The effect of density on MOE is quantified by employing Palka's empirical equation (Palka, 1973):

$$E_{i(t)} = E_{i(t-1)} \times \left(\frac{\rho_{i(t)}}{\rho_{i(t-1)}} \right)^p \qquad (14)$$

where $E_{i(t)}$ is the modulus of elasticity of layer i at new time t, $\rho_{i(t)}$ is the density of layer i at time t and $\rho_{i(t-1)}$ is the density of layer i at the old time *t-1*. p is the modifications constant for which Palka gives a value of 1.25. The strain in the mat occurring at the time t is calculated by:

$$\varepsilon_{(t)} = \frac{M_{(t_0)} - M_{(t)}}{M_{(t_0)}} \qquad (15)$$

where $\varepsilon_{(t)}$ = mat strain, $M_{(t_0)}$ = initial mat thickness, $M_{(t)}$ = mat thickness at time t.

The governing differential equation of a single Maxwell element given by Zombori (2001) is used to calculate the stress relaxation in different layers.

$$\frac{\partial \sigma}{\partial t} = E\frac{\partial \varepsilon}{\partial t} - \frac{1}{\tau}\sigma \qquad (16)$$

After integrating this, the stress change over a short time interval can be calculated by:

$$\Delta\sigma = E\Delta\varepsilon - \frac{1}{\tau}\sigma\,\Delta t \qquad (17)$$

Therefore the iteration formula for a single Maxwell element is

$$\sigma_{i(t)} = \sigma_{i(t-1)} + E_i(\varepsilon_{i(t)} - \varepsilon_{i(t-1)}) - \frac{\Delta t}{\tau_i}\sigma_{i(t-1)} \tag{18}$$

The effects of temperature and the moisture content on the relaxation of the element are taken into consideration by the method of reduced variables. The relaxation time (τ) is reduced with the temperature and moisture shift factor *a(T,MC)* as follows:

$$\sigma_{i(t)} = \sigma_{i(t-1)} + E_i(\varepsilon_{i(t)} - \varepsilon_{i(t-1)}) - \frac{\Delta t}{\tau_i a(T,MC)}\sigma_{i(t-1)} \tag{19}$$

The temperature and moisture content shift factor *a(T, MC)* can be determined by (Wolcott et al., 1990):

$$\log a(T,MC) = \alpha + \beta_1.T + \beta_2.T^2 + \beta_3.MC + \beta_4.MC^2 \tag{20}$$

in which T is the temperature in K and MC is the percentage moisture content. In equation (20), the coefficients are given by (Wolcott et al., 1990) as follows:
$\alpha = 8.9361$, $\beta_1 = 1.027\times10^{-1}$, $\beta_2 = 1.361\times10^{-4}$, $\beta_3 = 1.1908$, $\beta_4 = 2.598\times10^{-2}$
The second term on the RHS in the iteration formula (equation 19) is the induced stress due to elastic deformation, and the third term represents the stress relaxation as a function of time, temperature, and moisture content. The temperature and moisture content were calculated at the mesh points. The Maxwell ladder representing the material response was positioned between the mesh points, and therefore, the average of the temperature and moisture contents at the two bounding mesh points were used to calculate the shift factor.

RESULTS AND DISCUSSION

Case One- Simulation run for standard conditions

The program is written in the Matlab software. Due to the complexity of the problem, a modular programming style was chosen. The modular approach ensures the flexibility necessary for incorporation of changes and expansions in the future. In the simulation, the MDF mat is symmetrically divided into two halves and, once the calculation is complete, graphs of output properties for the complete thickness are generated. The parameters for a sample calculation are listed in Table 1 and the results plotted in Figures 1-4.

Table 1. Initial parameters for simulation

Panel density	650 kg/m^3
Weight of fibre	0.78 kg
Moisture content	10.5 %
Resin content	10.5 %
Platen temperature	180.2°C
Time steps	350
Press closing time	15 s
Average thickness	13 mm
Cycle used	Position
Number of layers in half board	10

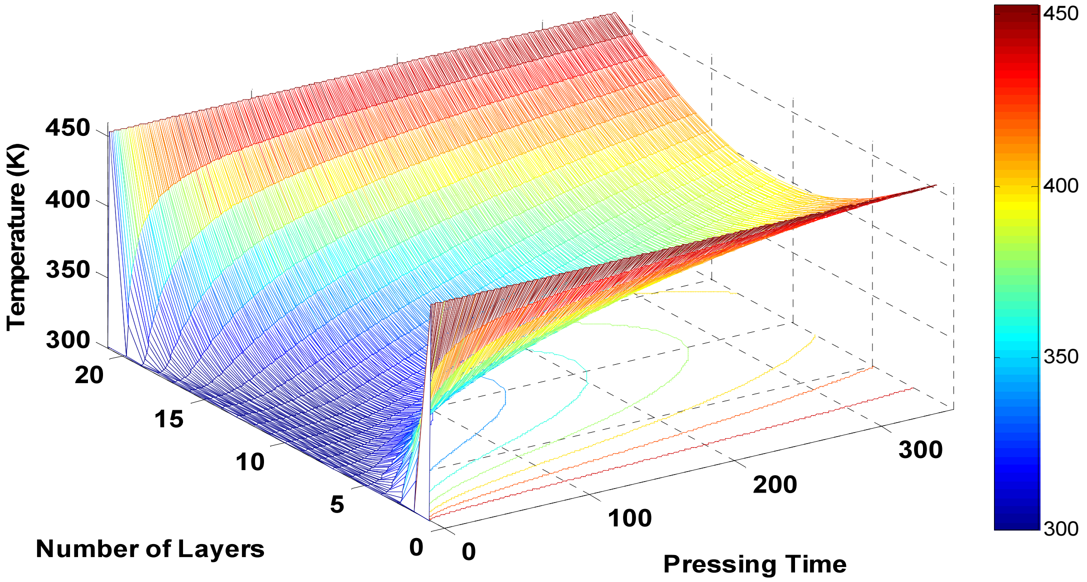


Figure-1 Change of temperature across thickness

Fig.1. shows the development of temperature across the mat thickness. Each mesh line represents one layer. The top surface layer reaches the platen temperature soon after entering the press. The core temperature increases slowly as shown in the figure.

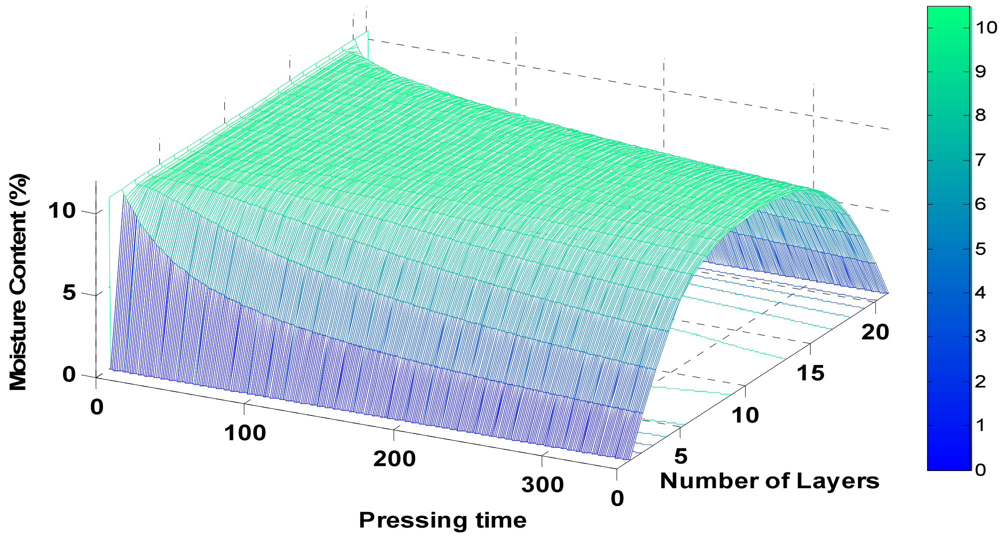


Figure-2 Change of moisture content across thickness

Fig. 2. represents the development of moisture content profile across thickness. The moisture content at the surface soon reaches zero, as the hot platen touches the surface. The highest moisture content is always at the centre, in the core region.

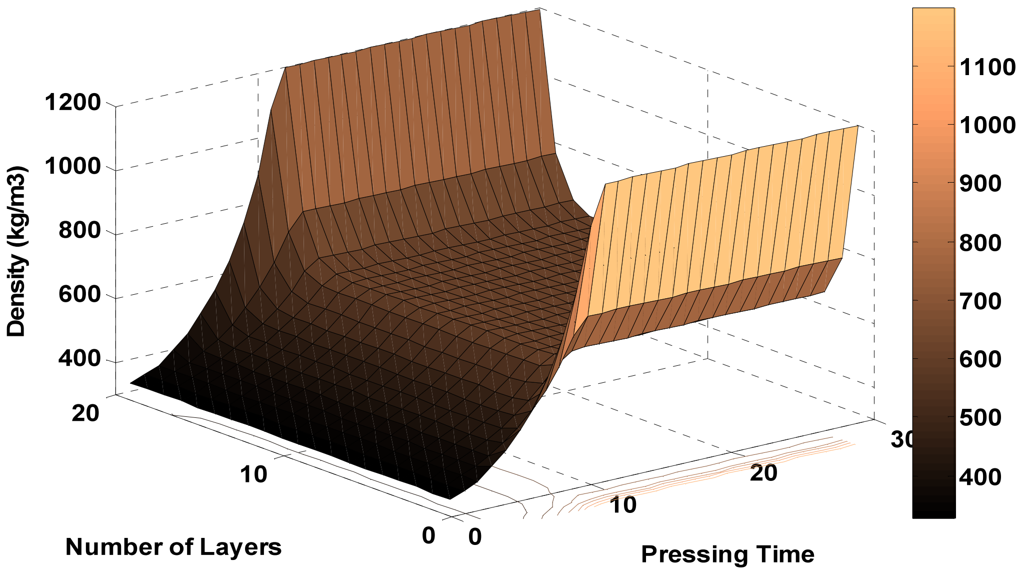


Figure-3 Density in different layers while pressing

Fig .3. Represents the density across the thickness. There is higher strain at the surface, which causes higher density at the surface relative to the core. Once the platen reaches its final position, there is only minor adjustment in the density distribution due to relaxation of fibre mat. The density profile for the first 30 seconds is shown in the figure.

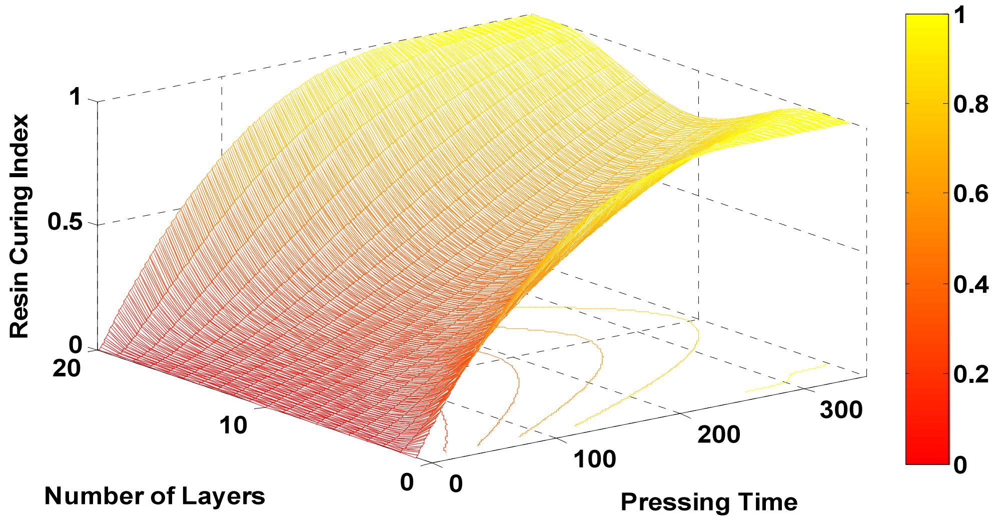


Figure-4 Extent of resin cure in different layers while pressing

Fig.4. shows the curing of resin across the thickness. The resin at the surface cures much faster due to high temperature and it takes much longer for the resin in the core region.

Validation of the model:

The results of the model are compared with the experimental results. The peak density for eight boards was calculated from the model are compared with the experimental data obtained by using the Proscan density profiler. It was observed that peak density from the model is higher than the experimental results. The core densities from the model follow the same trend as that of the experimental data.

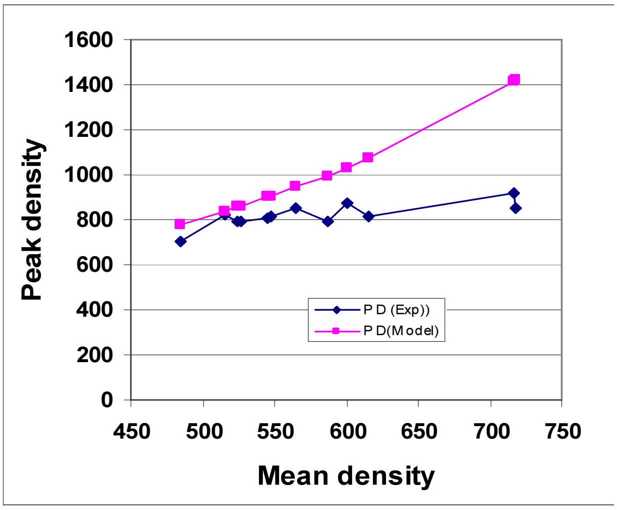
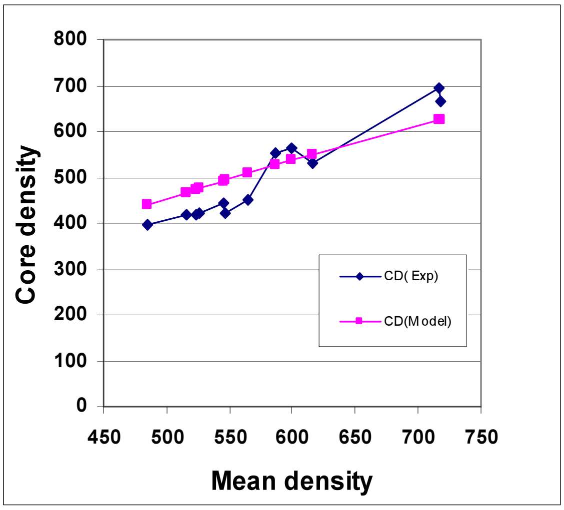


Figure-5. Comparison of peak density



Figurer-6 Comparison of core density

Comparison of Core temperature

Core temperature is one of the important parameters in the MDF manufacturing, as it controls the amount of resin cure in the board. In the beginning, the core temp from model is higher than the measured values, but later increases more slowly than the experimental value. Possible reasons for the differences are that the model over-estimates the initial movement of moisture from the regions near the platens and that the mat surface temperature does not immediately reach the platen temperature. There may be some effect from the heat generated by the compression of mat.

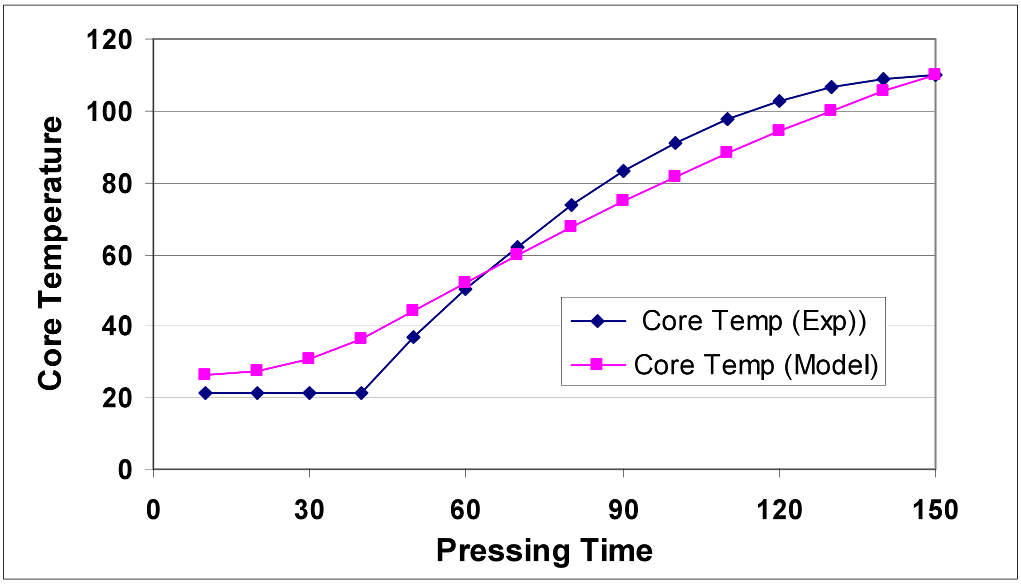
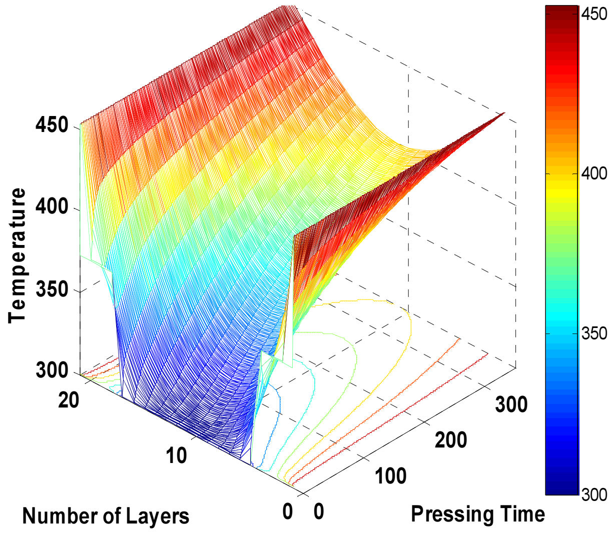


Figure-7 Comparison of core temperature from experiment and model

Case Two - Simulation run for steam injection pressing

In the second case, the simulation is done to predict the temperature and moisture content, for the steam injection pressing, or pre heated mat, having surface layer temperature 100 °C and moisture content 15 % and core temperature 27 °C and moisture content 8 %. See figures 8 and 9.



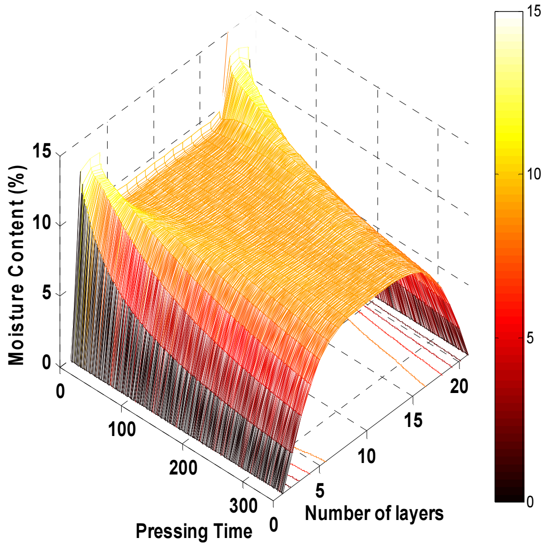
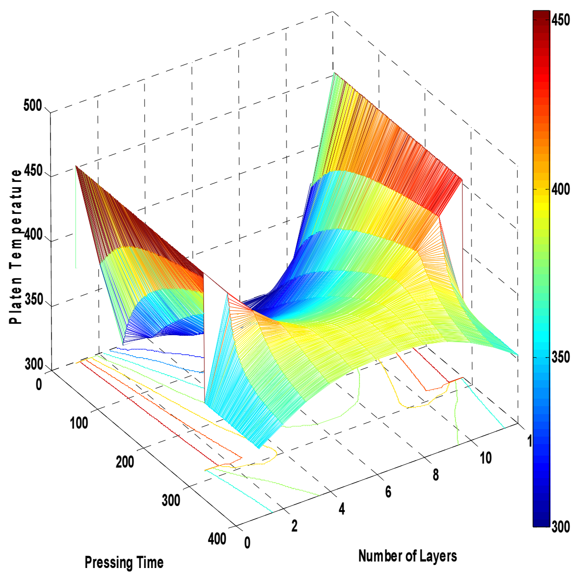


Figure-8 Change of temperature across thickness (Pre-heated mat with steam injection pressing)

Figure-9 Change of moisture content with time (Pre-heated mat)

Case Three - Simulation run for a cooling zone in the press: The platen temperature is reduced from 180 degree to 80 degree in last part of pressing (30%) of pressing time, the other simulation parameters remains the same. The simulation results are in figures 10 and 11.



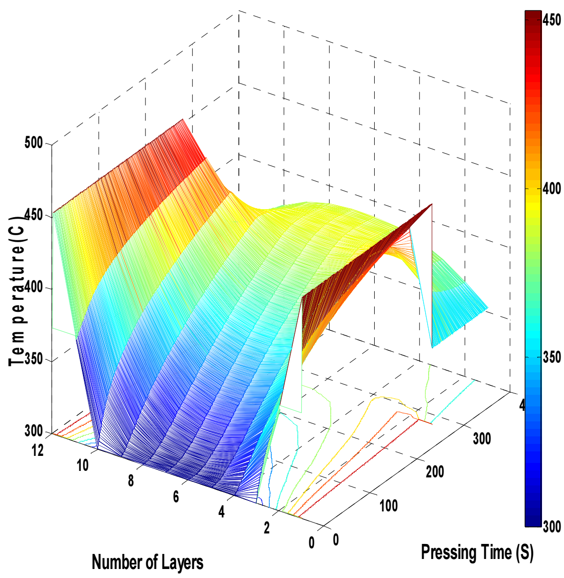


Figure-10 Change of temperature with time (Front view)

Figure-11 Change of temperature with time (Back view)

Figures 10 and 11 show the variation of temperature across the thickness for a continuous press with a cooling zone.

CONCLUSIONS

- The predicted core temperature from the model is higher than the experimental result at the beginning of the press cycle, but is slightly lower later in the pressing time.
- The predicted peak density from the model is higher than the experimental one, but the core density is the same for both.
- The simulation results from the model gives the results qualitatively and requires further refining to give more accurate quantatively results.
- Process modeling can be efficiently used to develop new production technologies and to improve the quality of board.
- Pre-heating of the mat reduces the time by 5 % to reach the same resin curing index in comparison to standard conditions

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NOMENCLATURE

c_u	specific heat of wood at current moisture content (J kg^{-1} K^{-1})
d	change in thickness in layer (m)
D	platen movement (m)
D_m	transverse diffusion coefficient for moisture movement (m^2 s^{-1})
E	modulus of elasticity (Pa)
H	moisture content of fibres
H_v	Latent heat of sorption from vapour to the bound water state per unit mass (J kg^{-1})
H_r	heat evolved from resin curing (J kg^{-1})
i	Number of layer
j	net vapour flux (kg m^{-2} s^{-1})
k_t	thermal conductivity (W m^{-1} K^{-1})
m	mass of vapour (kg s^{-1})
m_{ev}	evaporation rate (kg m^{-3} s^{-1})
M	thickness of mat (m)
MC	moisture content (%)
n	total number of layers
p_{sat}	saturated vapour pressure at given temperature
p	MOE modification constant (-)
q	conductive heat flux (J m^{-3} s^{-1})
S	summation of inverse MOE (Pa^{-1})
t	time (s)
T	temperature (K)
V	volume of mat layer (m^{-3})
x	distance from one mat surfaces (m)

Greek symbols

ε	strain (-)
ψ	relative humidity (-)
ρ	density (kg m^{-3})
σ	stress (Pa)
τ	time constant (s)

Subscripts

f	fibre
r	resin
u	at given moisture content
o	initial condition in the beginning

REFERENCES

BALL R D, SIMPSON I G and PANG S (2001): Measurement, modelling and prediction of equilibrium moisture content in *Pinus radiata* heartwood and sapwood. Holz als Roh-und Werkstoff 59: 457-462

CARVALHO L H and COSTA C (1998): Modelling and simulation of the hot pressing process in the production of medium density fibreboard (MDF). Chem. Eng. Comm. 170:1-21

CARVALHO L H, COSTA M R N and COSTA C A V (2001): Modelling rheology in the hot-pressing of MDF: comparison of mechanical models: Wood Fibre Science 33:395-411

DAY D L and NELSON G L (1965): Desorption isotherms for wheat. Trans. Amer. Soc. Agri. Eng 8: 293-297

HATA T, KAWAI S and SASAKI H (1990): Computer simulation of temperature behaviour in particle mat during hot pressing and steam injection pressing: Wood Science Technology: 24:65

HUBERT P and DAI C (1998): An object-oriented finite element processing model for oriented strand board wood composites. Proc. of the 13th Int. Conf. on Composite Materials, Paris, France

HUMPHREY P E (1982): Physical aspects of wood particle board manufacture. PhD Thesis. University College of North Wales, Bangor, UK

KAYIHAN F (1982): Simultaneous heat and mass transfer with local three phase equilibrium in wood drying. Proceedings 3rd International Drying. Symposium, J.C. Ashworth, Drying Research Limited, Wolverhampton, England Vol.1: 123-134

PALKA L C (1973): Predicting the effect of specific gravity, moisture content, temperature and strain rate on the elastic properties of softwoods. Wood Science and Technology 7: 127-141

PANG S (1997): Some considerations in simulation of superheated steam drying of softwood lumber. Drying Technology 15(2): 651-670

RESCH H, HOAG M L and ROSEN H N (1988): Desorption of yellow-poplar in superheated steam. Forest Products Journal 38(3): 13-18

STRICKLER M D (1968): High temperature moisture relations of grand fir. Forest Products Journal 18(4): 69-75

SUO S and BOWYER J L (1994): Simulation modelling of particleboard density profile. Wood Fibre Science 26(3): 397-411

THOMEN H (2000): Modelling the physical processes in natural fibre composites during batch and continuous pressing. PhD Dissertation, Oregon State University, USA.

USDA Forest Products Laboratory. (1999). Wood handbook. Wood as an Engineering Material. Forest Products Society, Madison, Wisconsin (USA)

WOLCOTT M P, KAMKE F A and DILLARD D A (1990): Fundamentals of flakeboard manufacture: viscoelastic behaviour of the wood component: Wood Fibre Science 22(4):345:361

ZOMBORI B G (2001): Modelling the transient effects during the hot pressing of wood based composites. PhD Dissertation, Virginia Polytechnic Institute and State University, USA